The "broken escalator" phenomenon: vestibular dizziness interferes with locomotor adaptation

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Running Title: Dizziness interferes with locomotor adaptation

Abstract

BACKGROUND: Although vestibular lesions degrade postural control we do not know the relative contributions of the magnitude of the vestibular loss and the subjective vestibular symptoms to locomotor adaptation in particular.

OBJECTIVE: To study how dizzy symptoms interfere with adaptive locomotor learning.

METHODS: We examined patients with contrasting peripheral vestibular deficits, vestibular neuritis in the chronic stable phase (n=20) and strongly symptomatic unilateral Meniere's disease (n=15), compared to age-matched healthy controls (n=15). We measured locomotor learning using the "broken escalator" aftereffect, simulated on a motorised moving sled.

RESULTS: Patients with Meniere's disease had an enhanced "broken escalator" postural aftereffect. More generally, the size of the locomotor aftereffect was related to how symptomatic patients were across both groups. Contrastingly, the degree of peripheral vestibular loss was not correlated with symptom load or locomotor aftereffect size. During the MOVING trials, both patient groups had larger levels of instability (trunk sway) and reduced adaptation than normal controls.

CONCLUSION: Dizziness symptoms influence locomotor adaptation and its subsequent expression through motor aftereffects. Given that the unsteadiness experienced during the "broken escalator" paradigm is internally driven, the enhanced aftereffect found represents a new type of self-generated postural challenge for vestibular/unsteady patients.

Introduction

Chronic unsteadiness and dizziness are common neurological complaints associated with a previous episode of vertigo and vestibular lesions [12, 21, 32]. Although unsteadiness and dizziness are not life threatening, they cause considerable social handicap and fear [47]. Vestibular neuritis and unilateral Meniere's disease are prototypical peripheral vestibular disorders that cause unilateral vestibular dysfunction and are associated with the development of chronic dizziness and unsteadiness. However, the degree and time course of the dizziness and vertigo differ critically [51]. Following the acute stage in vestibular neuritis, symptoms typically improve over weeks [12], whereas active Meniere's disease can result in continuous high levels of dizziness and vertigo due to persistent disease activity [10]. The traditional view is that long-term symptoms are related partly to the degree and type of peripheral vestibular loss and partly to central compensation - the process by which the "weighting" of sensory information from self-motion cues is adjusted [30]. However, in unilateral vestibulopathies there appears to be no association between the degree of vestibular loss and clinical outcome [3, 13, 38, 41].

The repercussions of poor outcome in vestibular disease on locomotion are poorly understood. In humans, locomotion requires the selection of appropriate motor programs to accommodate the range of everyday environmental demands. This is achieved across different timescales through adaptive learning processes [5]. One example of everyday adaptive locomotor learning is the balance adjustment required when stepping on to a moving escalator. When we encounter a familiar motor task, the brain generates sensorimotor predictions about the likely outcome and adapts motor plans accordingly [48]. This error-based learning process allows modification of strategies to maintain motor control and return behaviour to baseline performance [5]. In the broken escalator phenomenon, adaptive learning to stepping onto a moving platform leads to trunk overshoot and faster gait approach velocity than is required, when the individual subsequently steps onto a broken (stationary) escalator [17]. The characteristic stumble observed and transient sensation of dizziness or imbalance represents a locomotor aftereffect.

As one (vestibular neuritis) or many (Meniere's disease) episodes of intense vertigo represents a life-changing situation involving postural, psychological and brain structure changes [14, 15, 20], the broken escalator aftereffect is an ideal paradigm to study these central effects. Also, studying vestibular neuritis and Meniere's disease, with their different symptom loads and time scales, allows us to shed light on the mechanisms mediating postural imbalance in vestibular disease. On the basis of our and other's previous work [2, 9, 21, 40] one expects that vestibular patients will have greater sway during actual balance perturbations (MOVING sled trials on the broken escalator task) because they have objectively reduced vestibular sensory cues [34]. How much of this putative unsteadiness is actually due to the degree of vestibular loss or to the presence of subjective dizzy symptoms is however not known. Even less is known about the effects of subjective symptoms on locomotor adaptation and resulting aftereffects, both critical aspects of high order postural control.

We predict that patients with a diagnosis of Meniere's disease, or more generally those with higher dizziness levels, may have greater sway during balance perturbations (MOVING sled trials on the broken escalator task) over and above what is expected from the loss of vestibular input [34]. From a signal detection theory perspective, dizziness would reflect background vestibular 'noise' that could interfere with the fine sensory-motor tuning [11] required for locomotor adaptation. The high symptom load and central postural adjustments required for the generation of locomotor aftereffects may also be associated, either because dizzy symptoms interfere with postural control or because patients' symptoms partly arise from defective locomotor adaptive behaviour. We therefore explored the relationship between the degree of locomotor adaptive and anticipatory control using the locomotor aftereffect, degree of unilateral vestibular loss (caloric canal paresis) and clinical outcome (dizziness/vertigo symptoms) in patients with vestibular neuritis and with Meniere's disease.

Methods

Participants

Twenty patients with unilateral vestibular neuritis (5 female; mean age 54.8 years, SD=14.4), fifteen patients with unilateral Meniere's disease (5 female; mean age 48.9 years, SD=12.3) and fifteen healthy controls with normal vestibular function and no history of vertigo (6 female; mean age 55 years, SD=7.5) were recruited. Participants were age-matched (independent samples t-test $P \geq 0.096$).

Meniere's disease was diagnosed according to American Academy guidelines [1] and most patients conducted this experiment before participating in a trial of intratympanic injection for unilateral refractory Meniere's disease [39]. All vestibular neuritis patients had a typical history of sudden onset rotational vertigo lasting for several days, spontaneous unidirectional nystagmus, a positive head-impulse test, normal hearing and a clinically significant (>25%) unilateral caloric paresis, as previously described [11]. Vertigo onset took place at least six months previously, with no further attacks.

Equipment

The motion stimulus was provided by a linear sled running on a level track, powered by two linear induction motors [43] controlled by sled velocity as recorded with a tachometer. Anterior-posterior trunk position was measured using a Fastrak^{TM} system (Polhemus, VT, USA) that sampled at 250Hz. The movement sensor was secured at the level of the C7 vertebra to measure linear trunk displacement. Step timing was measured by contact plates under each foot and corroborated with a sled-mounted linear accelerometer.

Experimental design

Locomotor experiment

The experimental sequence involved three stages performed in this order: BEFORE (5 trials, stationary sled), MOVING (5 trials, moving sled) and AFTER trials (5 trials, stationary sled) [8].

In BEFORE, MOVING and AFTER trials, participants stepped from a stationary platform onto the sled, see Figure 1. Participants began by facing the direction of movement and initiated a step (right foot first) from a stationary stance, prompted by a single auditory beep, and continued their walk on to the sled. Participants were instructed that once both feet were on the sled they should stop and remain still [8].

Figure 1

In MOVING trials, the onset of sled motion was triggered by breaking an infra-red light beam when the subject stepped forward from the start position. This resulted in the sled moving, after a 600ms delay, a distance of 3.7m in 4.2s; (maximum velocity 1.4m/s achieved at 1.3s). Participants were asked to avoid using the handrails unless they truly felt they could fall. Upon completion of the MOVING trials, participants performed the AFTER trials. They were given the following instruction: "I want you to step onto the sled as before. Only this time it is not going to move" – and the motor was ostensibly turned off for reassurance. Each trial lasted 16 seconds after which the participant returned to the original starting position.

Outcome measurements

Clinical outcome

The Dizziness Handicap Inventory (DHI; total score, physical, functional and emotional subscales) [24] and the Vertigo Symptom Scale-short form (VSS; total score, autonomic-anxiety and vertigo-balance subscales) [52] were completed by all patients before the sled experiment.

The DHI (scored out of 100 points) comprised 25 questions measuring the physical, functional and emotional features of dizziness that the patient experienced in the preceding month to the experiment. The physical subscale (28pts) scored how physical movement affects dizziness, the functional subscale (36pts) scored how

dizziness affects everyday activities and the emotional subscale (36pts) scored how dizziness affects mental wellbeing (e.g., depression and relationships).

The VSS (scored out of 60pts) comprised 15 items measuring the frequency and severity of autonomic-anxiety (7 items, /28pts) and vertigo-imbalance symptoms (8 items, /32pts) in the previous month.

Degree of vestibular loss

To assess vestibular function, bithermal caloric irrigations (30 & 44°C) were performed at the time of the study (in the chronic phase in vestibular neuritis patients) and the percentage of canal paresis was calculated using Jongkees formula.

Locomotor outcomes

Trunk overshoot in the BEFORE and AFTER trials was taken as the maximum forwards trunk deviation relative to the final trunk position [26]. In MOVING trials, trunk sway was measured as the maximum backwards-forwards (peak-to-peak, see Figure 1) displacement after stepping onto the sled [26]. Gait velocity was calculated as the mean linear trunk velocity over a 0.5 second epoch prior to foot-sled contact. BEFORE trials 3-5 were averaged and used as baseline data in the analyses as previously described [26, 36]. BEFORE trials 1-2 were discarded as in this experiment they are regarded as *de facto* practice trials. As several studies have shown that the first AFTER trial reveals the locomotor aftereffect, we used this trial as the basis for measuring this aftereffect [26, 36, 37].

Statistical Analysis

As vestibular neuritis and Meniere's disease patients display different symptom and disease characteristics (i.e., inactive vs. active vertigo) we analysed vestibular neuritis and Meniere's disease data in isolation. Hence, we compared the performance of controls to each patient group in isolation to keep the analysis focused and to avoid complex statistical interactions. We then examined the relative performance of vestibular neuritis versus Meniere's disease.

To investigate locomotor adaptation in the MOVING trials, we employed mixed ANOVA (2x5 design) looking for main '*Group'* effects (2 levels) and main '*Trial Number'* effects (5 levels: 1-5). The rate of adaptation over MOVING trials 1-3 was determined by fitting a linear function to the trunk sway data and calculating the slope for each participant. We estimated the rate of adaptation based on MOVING trials 1-3 since this is where the maximum amount of learning takes place in controls before a plateau [9]. The rates of adaptation of the groups were compared using an independent samples t-test. To account for the possibility that participants with impaired motor learning may be more unsteady we calculated the degree of adaptation over MOVING trials 1-3 from trunk sway amplitude in MOVING trial 3/MOVING trial 1.

Mixed ANOVA (2x2 design) were also performed to investigate the presence of an aftereffect by comparing mean BEFORE trials 3-5 to AFTER trial 1 (*phase*, 2 levels:) and group differences (*group*, 2 levels). As before, we compared each patient group to controls first and then performance of vestibular neuritis versus Meniere's disease.

Post-hoc, two-tailed, statistics were performed when interactions were found. When post-hoc tests were performed, independent or paired-samples t-tests were used as appropriate and details of these are given in the text. Pearson's correlations and multiple linear regressions were performed to explore predictor variables. P-values<0.05 were considered significant.

Results

In the broken escalator task, motion data change markedly as a function of trial number in MOVING and AFTER trials but not in BEFORE trials. To negotiate the MOVING sled, gait velocity increases before foot-sled contact, and there is a forward trunk sway to shift the centre of mass anteriorly [26] (Figure 1). After the first MOVING trial, trunk sway reduces as subjects become accustomed to the motion of the sled and adapt their behavior accordingly. The underlying motor adaptation is manifest in the first AFTER trial as the locomotor aftereffect. Below, MOVING trials were analysed to investigate unsteadiness and adaptation, and AFTER trial 1, to investigate the locomotor aftereffect.

Locomotor adaptation (MOVING trials)

MOVING trials, in which participants were asked to step onto a moving sled, were used to compare adaptation between groups (i.e., the level of postural sway and gait velocity between successive trials). As shown in Figure 2, trunk sway was larger in patients compared to controls (Figure 2). All groups had a reduction of trunk sway with trial number demonstrating adaptation (significant *trial number* effect in two-way Mixed ANOVA, below). However, the rate of adaptation was quicker in controls compared to vestibular neuritis and Meniere's disease patients, as shown by a steeper adaptation gradient in MOVING trials 1-3, where maximal learning occurs (independent samples t-tests: vestibular neuritis vs Control, P=0.035); Meniere's disease vs Control, P=0.033).

A correlation was performed on MOVING trial data for the degree of adaptation in patients. The rationale was that excessive body sway may interfere with adaption to the moving task and, indeed, a reduced degree of adaptation in trials 1-3 was associated with higher average trunk sway in MOVING trials (average1-5) (r=0.35, P=0.041, Figure 3).

Figure 2

Vestibular neuritis vs. controls:

Trunk sway: Mixed ANOVA revealed significant effects for *trial number* (F[1,10]=17.5; P<0.001) and *group* (F[1,14]=11.9; P=0.005). A significant *trial number* by *group* interaction was found (F[1,10]=5.2; P=0.046) between vestibular neuritis and controls for the degree of sway across MOVING trials. Independent samples t-test showed that trunk sway was significantly larger in vestibular neuritis compared to controls in trials 2 (P=0.012), 3 (P=0.005) and 4 (P<0.001), Figure 2A.

Gait Velocity: Mixed ANOVA revealed no significant effects for *trial number* ($F[1,10]=1.91$; $P=0.19$), *group* ($F[1,14]=1.4$; $P=0.39$) or *trial number* by *group* interaction ($F[1,10]=0.53$; $P=0.76$), indicating no significant difference between vestibular neuritis and controls for gait velocity in MOVING trials.

Meniere's disease vs. controls:

Trunk sway: Mixed ANOVA revealed significant effects for *trial number* ($F[1,10]=8.16$; $P=0.009$) and *group* ($F[1,14]=7.96$; $P=0.019$). A significant *trial number* by *group* interaction was found ($F[1,10]=9.86$; $P=0.01$) between Meniere's disease and controls for the degree of sway across MOVING trials. Independent samples t-test showed that trunk sway was significantly larger in Meniere's disease compared to controls in trials 2 ($P=0.019$), 3 ($P=0.003$), 4 ($P<0.001$) and 5 ($P=0.042$), Figure 2B.

Gait velocity: Mixed ANOVA revealed no significant effects for *trial number* ($F[1,10]=3.2$; $P=0.076$), *group* ($F[1,14]=0.14$; $P=0.089$) or *trial number* by *group* interaction ($F[1,10]=1.61$; $P=0.24$), indicating no significant difference between Meniere's disease and controls for gait velocity in MOVING trials.

Vestibular neuritis vs. Meniere's disease:

There were no differences between vestibular neuritis and Meniere's disease patients for trunk sway or gait velocity in MOVING trials.

Trunk sway: Mixed ANOVA revealed a significant main effect for *trial number* ($F[1,10]=19.1$; $P<0.001$) showing adaptation, but not for *group* ($F[1,14]=0.03$; $P=0.87$). No significant *trial number* by *group* interaction was found ($F[1,10]=0.26$; $P=0.90$).

Gait velocity: Mixed ANOVA revealed no significant effects for *trial number* ($F[1,10]=0.41$; $P=0.80$), *group* ($F[1,14]=3.56$; $P=0.089$) or *trial number* by *group* interaction ($F[1,10]=0.66$; $P=0.64$).

Locomotor aftereffect (BEFORE vs. AFTER trials)

All groups showed an aftereffect, that is, they all produced a significantly larger trunk overshoot and faster gait velocity in the first AFTER trial compared to baseline (i.e., mean BEFORE trials 3-5, P<0.001, paired samples t-test).

Vestibular neuritis vs. controls

Trunk overshoot: Mixed ANOVA revealed no *group* difference between vestibular neuritis and controls (F[1,14]=0.57; P=0.48) but there was a significant *phase* effect (F[1,14]=22.2; P<0.001) showing a significant locomotor aftereffect for both groups (Figure 2A). No *phase* by *group* interaction was found, indicating no difference for the trunk aftereffect between vestibular neuritis and controls.

Gait velocity: There were significant main effects for *phase* (F[1,14]=44.2; P<0.001) and *group* (F[1,14]=4.77; P=0.047) in mixed ANOVA, indicating a gait velocity aftereffect and slower gait velocity in vestibular neuritis compared to controls (Figure 2A). No *phase* by *group* interaction was found (F[1,14]=3.71; P=0.079). Gait velocity was slower in vestibular neuritis compared to controls in BEFORE and AFTER phases.

Meniere's disease vs. controls

Trunk overshoot: Mixed ANOVA revealed significant effects for *phase* (F[1,14]=29.4; P<0.001) and *group* (F[1,14]=10.0; P=0.011). A significant *phase* by *group* interaction was found (F[1,14]=9.05; P=0.013) as trunk overshoot was significantly larger in Meniere's disease compared to controls in AFTER trial 1 (Figure 2B, P=0.024, independent samples t-test), but not in the BEFORE phase (trials 3-5, P=0.84).

Gait velocity: Mixed ANOVA revealed significant effects of gait velocity for *phase* (F[1,14]=78.3; P<0.001) and *group* (F[1,14]=6.42; P=0.024), reflecting a gait velocity aftereffect and slower gait velocity in MD. No *phase* by *group* interaction

was found (F[1,14]=3.67; P=0.076). Gait velocity was slower in Meniere's disease compared to controls in BEFORE and AFTER phases.

Vestibular neuritis vs. Meniere's disease

There were no differences between vestibular neuritis and Meniere's disease patients for trunk overshoot or gait velocity at baseline in BEFORE trials or in AFTER trial 1.

Trunk overshoot: Mixed ANOVA revealed a significant *phase* effect (F[1,14]=53.1; P<0.001) indicating a trunk locomotor aftereffect in both groups. Although the size of the trunk overshoot was numerically larger in Meniere's disease patients, *group* effects did not quite reach statistical significance (F[1,14]=3.9; P=0.077). No *group* by *phase* interaction was found (F[1,14]=3.61; P=0.087).

Gait velocity: Mixed ANOVA revealed no significant *group* effect (F[1,14]=0.88, P=0.37) but did show a significant *phase* effect (F[1,4]=58.8, P<0.001], indicating a gait velocity locomotor aftereffect in both groups. No *phase* by *group* interaction was found (F[1,14]=0.002; P=0.97).

Dizziness, vertigo and canal paresis

As shown in Table 1, DHI (vestibular neuritis=20.4, Meniere's disease=48.3) and VSS scores (vestibular neuritis=10.1, Meniere's disease=20.8) were twice as high in Meniere's disease compared to vestibular neuritis (both P<0.001, independent samples t-test). Higher VSS scores were associated with higher DHI scores (vestibular neuritis: Pearson's r=0.64, P=0.002; Meniere's disease: Pearson's r=0.72, P=0.002) indicating agreement between the clinical scales.

Table 1

Caloric paresis (for vestibular neuritis=33.5%, SD=23.2; Meniere's disease=43.8%, SD=25.2) was marginally larger in Meniere's disease compared to vestibular neuritis (Table 1, P=0.038, independent samples t-test), but there was no correlation between caloric paresis and DHI scores (vestibular neuritis: Pearson's r=0.11, P=0.65; Meniere's disease: Pearson's r=0.37, P=0.17) or between caloric paresis and VSS scores in vestibular neuritis (Pearson's r=0.08, P=0.78) in line with previous work [12, 38] or in Meniere's disease. The correlation between caloric paresis and VSS scores approached significance in Meniere's disease: (Pearson's r=0.35, P=0.055).

Next, we investigated whether overall symptom load impacts on locomotor parameters. When there was a significant association, we isolated the effect using DHI (physical, functional and emotional) or VSS subscales (autonomic-anxiety and vertigo-imbalance) as appropriate.

Vestibular neuritis:

11/21 vestibular neuritis patients were poorly compensated i.e., DHI score >20 [38]. On the other end of this spectrum 6 patients were virtually symptom free, including 4 who scored "0" on the DHI.

MOVING trials: Higher DHI (Pearson's r=0.40, P=0.041, Figure 4A) and VSS scores (Pearson's r=0.53, P=0.016) were associated with larger mean trunk sway in MOVING trials, specifically higher functional DHI scores (Pearson's r=0.57, P=0.009) with a trend relationship to higher autonomic-anxiety VSS scores (Pearson's r=0.36, P=0.053). Mean trunk sway was not related to caloric paresis. The rate of adaptation and the degree of adaptation were not associated with DHI, VSS or caloric paresis. Mean gait velocity in MOVING trials was not associated with DHI, VSS scores or caloric paresis.

AFTER trial 1: A larger trunk aftereffect correlated to higher DHI scores (Pearson's r=0.53, P=0.016, Figure 5A), specifically higher functional DHI scores (Pearson's r=0.60, P=0.005). The association between the trunk aftereffect and emotional DHI scores approached significance (Pearson's r=0.41, P=0.06; Figure 6). Deeper analysis showed a significant correlation between the trunk aftereffect and

emotional DHI scores after the four asymptomatic (i.e., patients that did not experience emotional effects from their dizziness; DHI=0) vestibular neuritis patients were omitted from analysis (Pearson's r=0.51, P=0.041). There was no association between the size of the trunk aftereffect and caloric paresis. The gait velocity aftereffect was not associated with DHI, VSS scores or caloric paresis.

Meniere's disease:

In Meniere's disease, more frequent vertigo attacks in the preceding six-months were associated with higher VSS (Pearson's r=0.61, P=0.020) and DHI scores (Pearson's r=0.53, P=0.041).

MOVING trials: Higher DHI scores were associated with larger mean trunk sway in MOVING trials 1-5 (Pearson's r=0.52, P=0.040, Figure 4B). Specifically, larger mean sway was associated with higher emotional DHI scores (Pearson's r=0.61, P=0.012). Mean trunk sway was not related to caloric paresis. The rate of adaptation and the degree of adaptation were not associated with DHI, VSS or caloric paresis. Mean gait velocity in MOVING trials was not associated with DHI, VSS scores or caloric paresis.

After trial 1: A larger trunk locomotor aftereffect correlated to higher DHI scores (Pearson's r=0.55, P=0.016, Figure 5B), specifically higher emotional (Pearson's r=0.62, P=0.012, Figure 6) and functional DHI scores (Pearson's r=0.50, P=0.018). A larger locomotor aftereffect also correlated to higher VSS scores (Pearson's r=0.53, P=0.041), particularly the autonomic-anxiety (Pearson's r=0.52, P=0.045) but also the vertigo-imbalance subscales (Pearson's r=0.53, P=0.036). The gait velocity locomotor aftereffect was not associated with DHI, VSS scores or caloric paresis.

Figure 3

Figure 4

Figure 5

Figure 6

Discussion

In this study we investigated patients with two extreme types of peripheral vestibular disorders, vestibular neuritis in a chronic, stable phase and refractory Meniere's disease with frequent vertigo attacks. We wanted to know how disease course (single vs. recurrent vertigo attacks), subjective clinical status (questionnaires) and degree of peripheral vestibular loss (canal paresis) affect both motor adaptation to a challenging gait task (MOVING trials) and the expression of such adaptation, as measured by the locomotor aftereffect (AFTER trials). The rationale for this study were recent observations that clinical outcome in vestibular disease appears more dependent on central processing mechanisms than on the magnitude of the peripheral vestibular loss [11, 13]. However, in contrast to most previous studies investigating such central mechanisms, largely focusing on *perceptual* processing, here we investigated complex *motor* mechanisms, specifically locomotor adaptation and aftereffect expression. Although a reflex role for the vestibular system in postural control is well established, whether symptomatic recovery from a vestibular insult is related to locomotor adaptation is not known. Understanding these central processes, which in principle are amenable to retraining, will likely impact on rehabilitation in these patients. With this in mind, a main finding in our study is that the degree of peripheral vestibular loss has little bearing on the postural and locomotor responses investigated. In contrast, the underlying cause of the vestibular deficit, Meniere's disease or vestibular neuritis,

does influence motor parameters although this appears to be dictated by the degree of dizziness/vertigo experienced and its emotional impact on the individual patient. The findings imply that higher order (presumably cortical) locomotor mechanisms are modulated by subjective feelings of dizziness or instability.

AFTER trials – the effect of dizziness on locomotor aftereffects

We found that a larger locomotor aftereffect was associated with higher levels of dizziness or vertigo across both patient groups. This means that, when facing a potentially provocative situation known to have caused loss of balance (in this case the previously moving platform), the more symptomatic patients release a large "pre-emptive" postural adjustment, which is the basis of the locomotor aftereffect [49]. Association or statistical correlation however does not mean causality nor does it establish the direction of this association; does a high symptom load modulate aftereffect expression or, rather, does an exaggerated aftereffect contribute to higher levels of subjective symptoms?

Although this is a difficult question to answer, a previous study using the same locomotor paradigm in normal subjects could be of help in addressing this issue. In that study we investigated different levels of task difficulty by varying sled velocity during the MOVING trials. We observed that faster sled velocities induced higher levels of fear/anxiety and lack of confidence in being able to complete the task which, in turn, led to a larger locomotor aftereffect [18]. On this basis, and on the knowledge that anxiety and lower balance confidence levels facilitate chronic dizziness [13], our current data suggests that higher dizziness scores modulate locomotor adaptation and aftereffect expression rather than the other way round.

This is supported by our regression analysis indicating that greater trunk sway during the MOVING trials and a larger locomotor aftereffect relate to total dizziness scores and to the emotional subscores. A more detailed assessment of anxiety, fear and arousal would have been desirable and this constitutes a partial limitation of our study. Functional connectivity between limbic and postural structures in the CNS - including the parabrachial nucleus, central amygdaloid nucleus, infralimbic cortex, and hypothalamus [4, 19] - could underpin the effects

that subjective symptoms and emotional aspects of balance have on adaptive locomotor control.

The ‘broken escalator’ locomotor aftereffect is unique in that despite subjects being consciously aware that the walking surface will remain stationary, they are unable to suppress the (now inappropriate) learnt motor response, mirroring the real-life experience of commuters facing a broken escalator [7, 44]. In the presence of a vestibular lesion it would seem beneficial to rely more on anticipatory, ‘open loop’ or pre-emptive postural adjustments. However, our experiments show that, in doing so, patients can experience self-generated unsteadiness when pre-emptive postural adjustments are released inappropriately, as seen during the ‘broken escalator’ example [50]. The finding of an increased locomotor aftereffect in subjects with high dizziness scores represents a new category of postural threat for these patients, in this case self-initiated or self-imposed. A proportion of our VN and MD patients with high DHI likely manifest features of persistent postural perceptual dizziness (PPPD) – a disorder usually emerging following an acute peripheral vestibulopathy in susceptible individuals [49]. Those who develop PPPD after an acute event show persistent high visual dependence, high anxiety and hypervigilance to balance afferents compared with those who recover well. Our findings are therefore of wider relevance to vestibular disorders with a strong psychological root and suggest that psychological variables may induce inappropriate pre-emptive postural adjustments in the face of perceived postural threat, paradoxically leading to greater unsteadiness.

Motor aftereffects are the result of a period of motor learning or adaptation to a perturbation. Indeed, the presence of an aftereffect is considered proof that learning or adaptation has taken place [29]. Therefore, the larger locomotor aftereffect recorded in Meniere’s disease patients could be the result of increased postural sway during MOVING trials. However, this is unlikely because vestibular neuritis patients also had significantly enhanced sway during MOVING trials and yet produced a similarly sized locomotor aftereffect to controls. In fact, even bi-labyrinthine defective patients produce a similar locomotor aftereffect to controls despite a two-fold increase in sway during MOVING trials [9]. A second possibility to explain the larger locomotor aftereffect is the influence of higher-order

mechanisms and, indeed, there are several lines of evidence indicating cortical involvement in the generation of this aftereffect. Previous studies have shown that specific components of motor learning in this task are the result of open-loop predictive behaviour [43] and that the size of the locomotor aftereffect is related to the perceived risk of the task [18] and the sense of self-agency involved [45]. Moreover, the locomotor aftereffect can be modulated with transcranial cortical stimulation [26] or by observing an actor's gait, likely engaging 'mirror neuron' systems [37]. We therefore propose that the enhanced locomotor aftereffect in very symptomatic patients reflects altered cortical processing during retention and expression of the learnt motor task, due to the influence of dizziness. Such central modulation of the locomotor aftereffect by subjective symptoms mirrors the effects of anxiety and personality traits observed upon motor learning retention, whereby participants reporting higher levels of stress and anxiety or those with extrovert personalities demonstrate greater retention in certain motor learning tasks [16, 22, 25].

MOVING trials – adaptation to a physically challenging task

Two findings were observed during the actual physical perturbation, that is, during the MOVING trials. Firstly, we observed that the degree of instability (trunk sway) was larger in patients with higher symptom levels. As with any other outcome in this study, instability levels were not associated with the degree of canal paresis. Thus, the motor responses to both the MOVING and the AFTER trials are less dependent on an 'objective' vestibular parameter such as canal paresis, indicative of how severe the vestibular damage is, than on 'subjective' parameters indicative of how dizzy those patients feel. This vestibulo-postural result thus parallels the lack of correlation observed between vestibulo-ocular reflex function and long-term clinical outcome [13, 38]. Clinicians should reflect on whether too much emphasis is currently being placed on pharmacological treatments aimed at modestly improving canal paresis, e.g. steroids in vestibular neuritis [28], with little or no bearing on symptomatic outcome, versus other treatment resources such as rehabilitation and confidence building.

The second observation during the MOVING trials is that patients adapted to the perturbation more slowly than controls. When participants repeated the MOVING trials, the performance of healthy individuals improved rapidly by the second and third attempts as they generated more accurate predictive postural responses [8, 46] and reached a plateau [8, 43]. In patients, we observed a slower rate of adaptation compared to controls, irrespective of dizziness/vertigo symptoms or vestibular function, as also observed previously in bi-labyrinthine defective patients [9]. However, we observed a relationship between a reduced degree of adaptation to the MOVING sled and average trunk sway levels in the MOVING trials, that is, the more unsteady the patient is, the less he/she learns the task (Figure 3). Thus, although it is not clear what dictates the degree of locomotor adaptation in this specific paradigm, multifactorial, non-specific effects seem to be at play. It seems that *any* abnormality in the postural control system associated with a degree of unsteadiness can interfere with the degree of adaptation to a moving surface stimulus [21, 33, 35]. This agrees with the view that the fine-tuning required for motor adaptation is critically hindered by the presence of "noise" in the sensory and motor systems [6].

In both the BEFORE and AFTER phases, the stability of patients seems to have been maintained at the cost of gait velocity, in line with previous work [2, 27]. The slower gait velocity of patients in BEFORE and AFTER trials may thus relate to precautionary trade-off behaviour. This tallies with the enhanced locomotor aftereffect, an aftereffect that has been described as a "just in case" pre-emptive postural adjustment – anticipatory mechanisms release a small postural adjustment which, although inappropriate for a stationary support surface, would be useful 'just in case' the surface moved [50]. Thus, both the presence of an enhanced locomotor aftereffect and reduced gait velocity during the stationary sled trials may represent precautionary behaviour induced by dizziness or a sense of imbalance, concordant with our previous findings in bi-labyrinthine defective patients [9]. Of note, however, gait approach velocities were similar across all groups during MOVING trials, indicating that gait could be appropriately calibrated to the velocity of the moving sled if critically needed to avoid a fall. This shows that vestibular neuritis and Meniere's disease patients are capable of adjusting gait parameters when facing a threatening external perturbation.

Another limitation of our study is that the caloric test is the sole measure of vestibular function. Additional measures of vestibular function from sinusoidal harmonic acceleration or the video Head-Impulse Test might have afforded insight into the relationship between measures of vestibular compensation and locomotor adaptation. However, it should be pointed out that the sinusoidal harmonic test [42] and Head Impulse test [31] can produce relatively normal results in Meniere's disease and in chronic vestibular neuritis [13, 38, 41], despite the range of locomotor responses that were observed.

In conclusion, our findings suggest that dizziness/vertigo symptoms may bias the selection of locomotor programs in favour of an over-cautious motor strategy. Symptoms interact with central motor control mechanisms and modulate output accordingly. The predictive 'open loop' nature of such process can occasionally lead to errors. In situations where pre-emptive or anticipatory postural adjustments are followed by a physical perturbation, such an approach might be beneficial. However, excessive postural anticipation not followed by a physical perturbation self-generates unsteadiness in patients; an unsteadiness which, as in a vicious circle, is larger in the more symptomatic patients. Such high-order mechanisms might contribute to increased unsteadiness across a variety of vestibular and neurological gait disorders.

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Figure Captions

Figure 1: Experimental design. The figure shows the experimental sequence (from left to right) and model trunk data from a Fastrak sensor placed on C7. All groups performed BEFORE, MOVING and AFTER trials in which subjects step, leading with the right leg, from a fixed surface to a sled which is either stationary or moving. Forward sway was measured in stationary sled phases (BEFORE and AFTER trials) as the maximum forwards deviation of the trunk relative to the final 3s of the trial. Trunk sway in the MOVING phase was measured as the peak-to-peak forwards movement. In all phases (BEFORE, MOVING and AFTER) approach velocity was measured in a 0.5s epoch prior to foot-sled contact. In the MOVING phase, stepping onto the moving sled for the first time results in backwards sway. A significant locomotor aftereffect is characterised by a forward trunk sway overshoot (12cm in the representative trace in the figure) and faster gait velocity in AFTER trials, despite explicit information that the sled will not move.

Figure 2. Locomotor performance of control and patient groups. Mean ± Standard Error (SEM) A. Vestibular neuritis vs. controls and B. Meniere's disease vs. controls during BEFORE, MOVING and AFTER phases for trunk sway (top row) and gait velocity (bottom row). The horizontal axis shows the trial number (1-5). The trunk sway aftereffect (AFTER trial 1) was larger in Meniere's disease compared to controls. Gait velocity was slower in patients compared to controls in both the BEFORE and AFTER phases. Significant differences between VN and controls and MD and controls are shown with asterisks *P<0.05, **P<0.01, ***P<0.001.

Figure 3: Association between the degree of adaptation (i.e., change in trunk sway between MOVING trials 1-3) and mean trunk sway across MOVING trials. The figure shows that subjects with larger levels of overall trunk sway have a slower rate of adaptation. Asterisk = P<0.05.

Figure 4: Associations between mean trunk sway size across MOVING trials and Dizziness Handicap Inventory (DHI) score for A. Vestibular neuritis and B. Meniere's disease. Together, A and B show that the size of mean trunk sway correlates with the level of subjective dizziness as shown by the Pearson's

r correlation coefficient score. Asterisks display the level of significance, where *P<0.05.

Figure 5: Associations between trunk aftereffect size (AFTER trial 1) and Dizziness Handicap Inventory (DHI) score for A. Vestibular neuritis and B. Meniere's disease. Together, A and B show that the size of the trunk aftereffect correlates with the level of subjective dizziness as shown by the Pearson's r correlation coefficient score. Asterisks display the level of significance, where *P<0.05.

Figure 6: Association between aftereffect size and emotional Dizziness Handicap Inventory (DHI) scores for Meniere's disease and vestibular neuritis patients. The correlation was significant in Meniere's disease (Pearson's r=0.62, P=0.012) but not for vestibular neuritis patients (Pearson's r=0.41, P=0.06). However, when asymptomatic vestibular neuritis patients were omitted (i.e. score = 0; n=4), a significant correlation is present (Pearson's r=0.51, P=0.041). The line of best fit is shown for Meniere's disease in black and vestibular neuritis in grey.

Tables

Meniere's disease patients (N)	Number of attacks in previous six months	Total DHI Score	Total VSS Score	Caloric paresis (%)	**Vestibular Neuritis patients** (N)	Time since acute episode (months)	Total DHI score	Total VSS Score	Caloric Paresis (%)
1	8	22	8	18	1	13	8	18	73
2	20	56	33	62	2	11	0	0	16
3	35	82	32	50	3	15	6	10	18
4	18	80	26	87	4	12	4	0	21
5	25	34	22	81	5	12	26	14	5
6	60	62	40	4	6	12	8	5	36
7	12	36	20	20	7	13	38	12	49
8	10	72	19	60	8	12	18	12	5
9	4	38	10	32	9	7	36	15	13
10	24	80	26	54	10	6	40	12	11
11	2	12	1	55	11	9	12	13	43
12	8	36	18	29	12	12	42	22	75
13	10	50	18	79	13	12	24	15	62
14	15	42	23	26	14	24	2	0	21
15	8	22	16	17	15	24	40	8	0
					16	36	12	1	28
					17	40	24	6	59
					18	12	22	8	50
					19	30	38	22	52
					20	18	8	8	32
Mean	19.8	48.3	20.8	43.8	Mean	16.5	20.4	10.1	33.5
SD	14.8	22.9	10.0	25.2	SD	9.4	14.5	6.8	23.2

Table 1: Patient details: Dizziness scores (DHI) and Vertigo scores (VSS) were higher overall in Meniere's disease patients compared to vestibular neuritis. All tests were performed at follow-up.

Figure 1

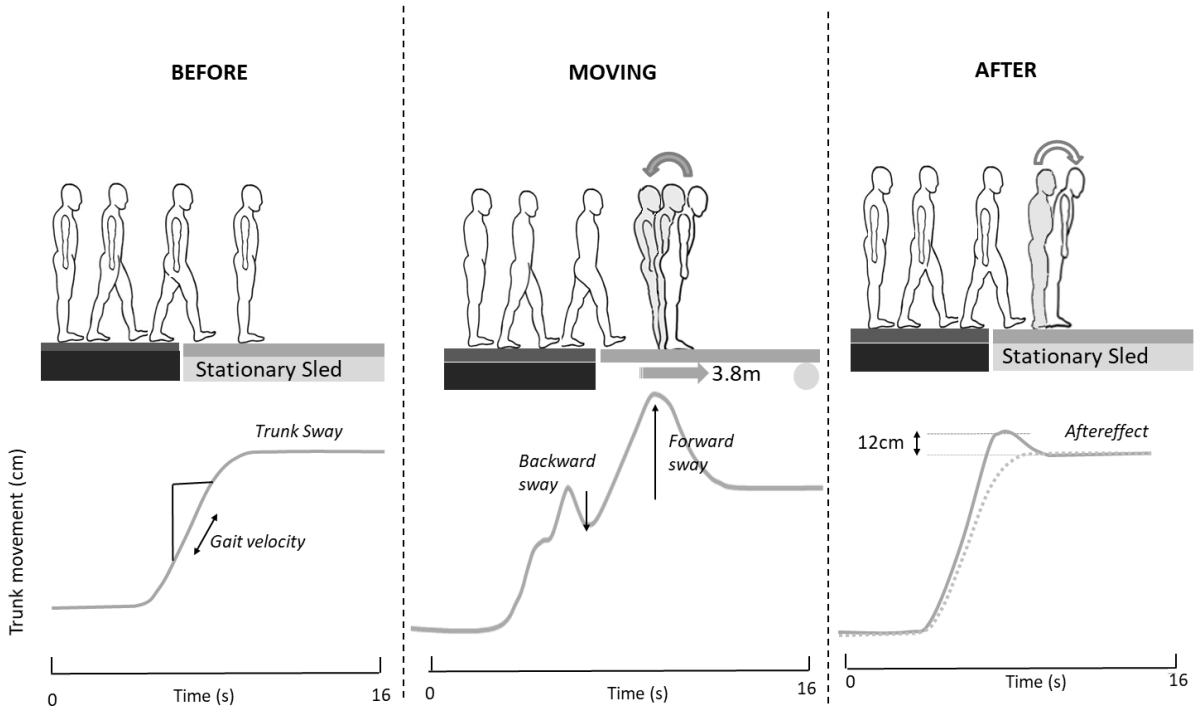

BEFORE
MOVING
AFTER
Stationary Sled
3.8m
Stationary Sled
Trunk Sway
Gait velocity
Trunk movement (cm)
Backward sway
Forward sway
12cm
Aftereffect
0
Time (s)
16
0
Time (s)
16
0
Time (s)
16

Figure 2

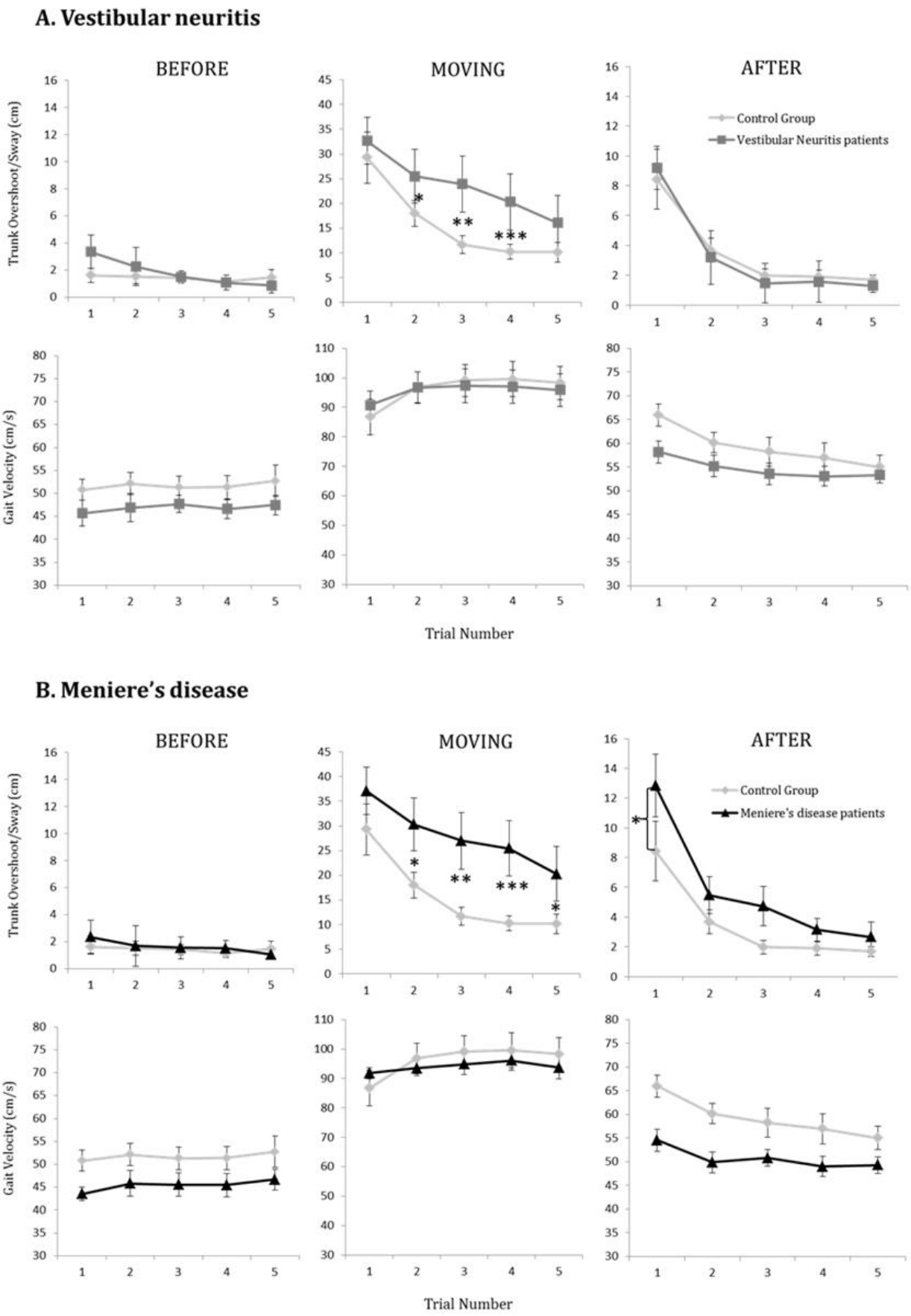

A. Vestibular neuritis
BEFORE
MOVING
AFTER
Trunk Overshoot/Sway (cm)
Gait Velocity (cm/s)
Control Group
Vestibular Neuritis patients
Trial Number
B. Meniere's disease
BEFORE
MOVING
AFTER
Trunk Overshoot/Sway (cm)
Gait Velocity (cm/s)
Control Group
Meniere's disease patients
Trial Number

Figure 3

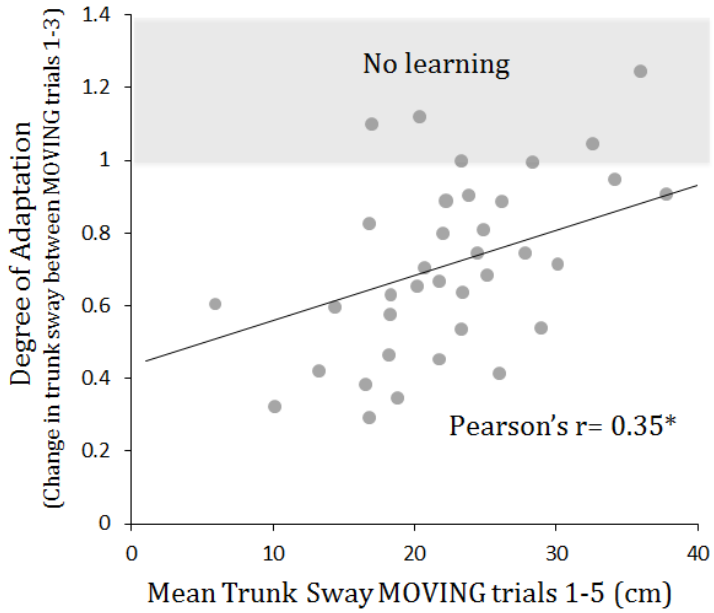

No learning
Pearson's r= 0.35*
Degree of Adaptation
(Change in trunk sway between MOVING trials 1-3)
Mean Trunk Sway MOVING trials 1-5 (cm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
10
20
30
40

Figure 4

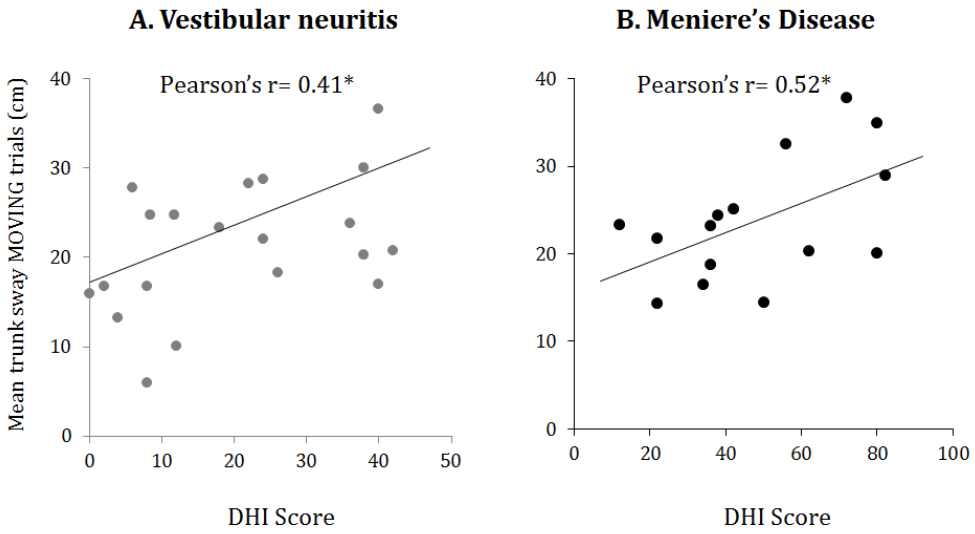

A. Vestibular neuritis
Pearson's r= 0.41*
Mean trunk sway MOVING trials (cm)
DHI Score
B. Meniere's Disease
Pearson's r= 0.52*
DHI Score

Figure 5

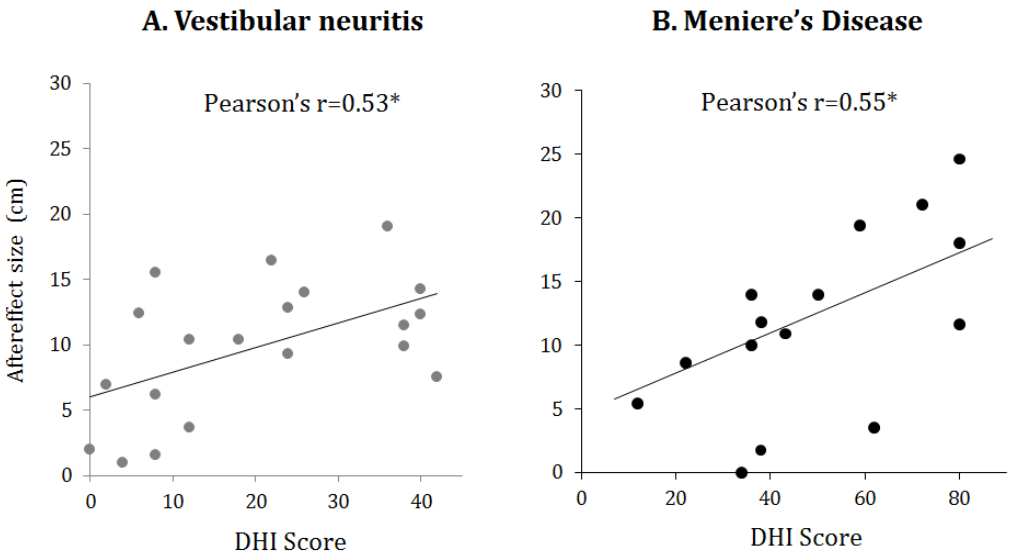
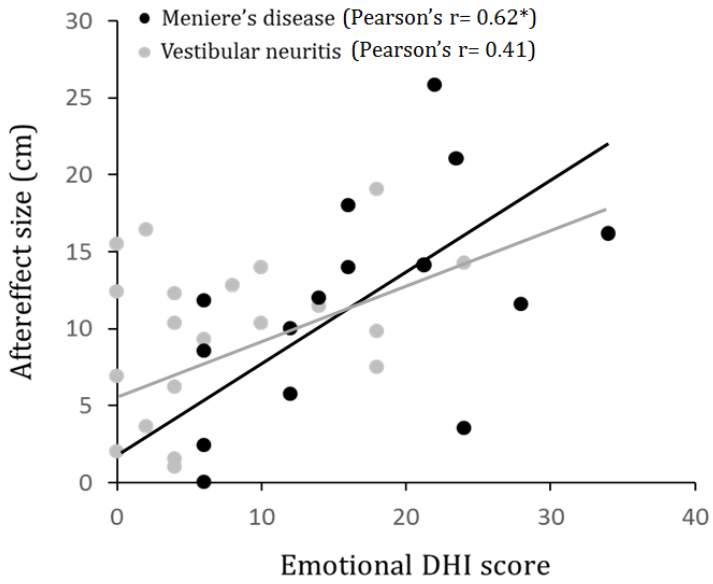

A. Vestibular neuritis
Pearson's r=0.53*
Aftereffect size (cm)
DHI Score
B. Meniere's Disease
Pearson's r=0.55*
DHI Score

Figure 6


Meniere's disease (Pearson's r= 0.62*)
Vestibular neuritis (Pearson's r= 0.41)
Aftereffect size (cm)
Emotional DHI score
0
5
10
15
20
25
30
0
10
20
30
40